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Climate warming and management impact on the change of phenology of the rice-wheat cropping system in Punjab, Pakistan

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ABSTRACT

The phenological changes of a long-term observed rice-wheat system (RWS) were used to determine the relationships among management practices, climate change, and crop phenology to devise adaptation strategies for RWS for mitigating the potential impact of climate change. The study comprised of 10 sites of observed and simulated rice-wheat system phenological data for the historical period from 1980 to 2014 in Punjab, Pakistan. The observed climate warming from sowing or/transplanting to maturity ranged from 0.50 to 1.20 °C decade^{-1} for rice and 0.77 to 1.07 °C decade^{-1} for wheat. The observed rice phenological stages were advanced by an average of 7.90 (sowing (S)), 6.60 (transplanting (T)), 4.30 (panicle initiation (PI)), 5.00 (anthesis (A)) and 6.40 (maturity (M)) days decade^{-1}, while rice phenological phases were reduced by an average of 1.4 (S-T), 6.40 (T-M), 3.00 (PI-A), 4.70 (PI-M) and 4.10 (A-M) days decade^{-1}. For wheat, sowing (S) and emergence (E) dates were delayed by an average of 9.50 and 1.30 days decade^{-1}, while anthesis (A) (5.30 days decade^{-1}) and maturity (M) (5.40 days decade^{-1}) dates were advanced. The duration of wheat phenological phases was reduced by an average of 5.50 (S-A), 5.70 (S-M) and 4.60 (A-M) days decade^{-1}. The S and E dates were positively correlated with increasing temperature and the A and M dates and phases (S-A, A-M, and S-A) were negatively correlated with increasing temperature for all study locations. Using the CSM-CERES-Rice and CSM-CERES-Wheat models for standard, field-tested cultivars of rice and wheat for all locations for the 35-year period showed that the simulated phenology stages were earlier with climate warming compared to the observed phenology stages. A significant portion of the negative impact of warming on rice (35%) and wheat (21%) was offset by growing new cultivars that had higher thermal time requirements. Thus, to mitigate climate change impacts, new cultivars for RWS should be introduced that require higher growing degree days and have a high temperature tolerance.

1. Introduction

Climate change threatens agricultural productivity globally, regionally, and locally (Hu et al., 2005; Ding et al., 2006; Tao et al., 2006; Iqbal et al., 2009; Semenov, 2009; Liu et al., 2010; van Ogtrop et al., 2014; Ahmad et al., 2015; Abbas et al., 2017; Liu et al., 2018). The 2000s was the warmest decade and 2016 was the warmest year. The climate warming trend for the observed mean temperature ranges from 0.78 to 1.5 °C during the past three decades, and is predicted to be 2 to 4 °C at the end of this century (Rasul et al., 2012; IPCC, 2014; Bokhari et al., 2017; Abbas et al., 2017). It is expected that this rise in temperature will have a dramatic impact on agriculture, especially for arid and semi-arid regions including the study sites, i.e., Sialkot, Gujranwala, Hafizabad, Sheikhupura, Nankana Sahib, Multan, Lodhran, Bahawalpur, Bahawalnagar and Rahim Yar Khan in Punjab, Pakistan (Ahmed et al., 2011; Rasul et al., 2012; Amin et al., 2018; Ahmad et al., 2017b; Abbas et al., 2017; Tariq et al., 2018).

The phenology of crop plants affects total biomass and grain yield

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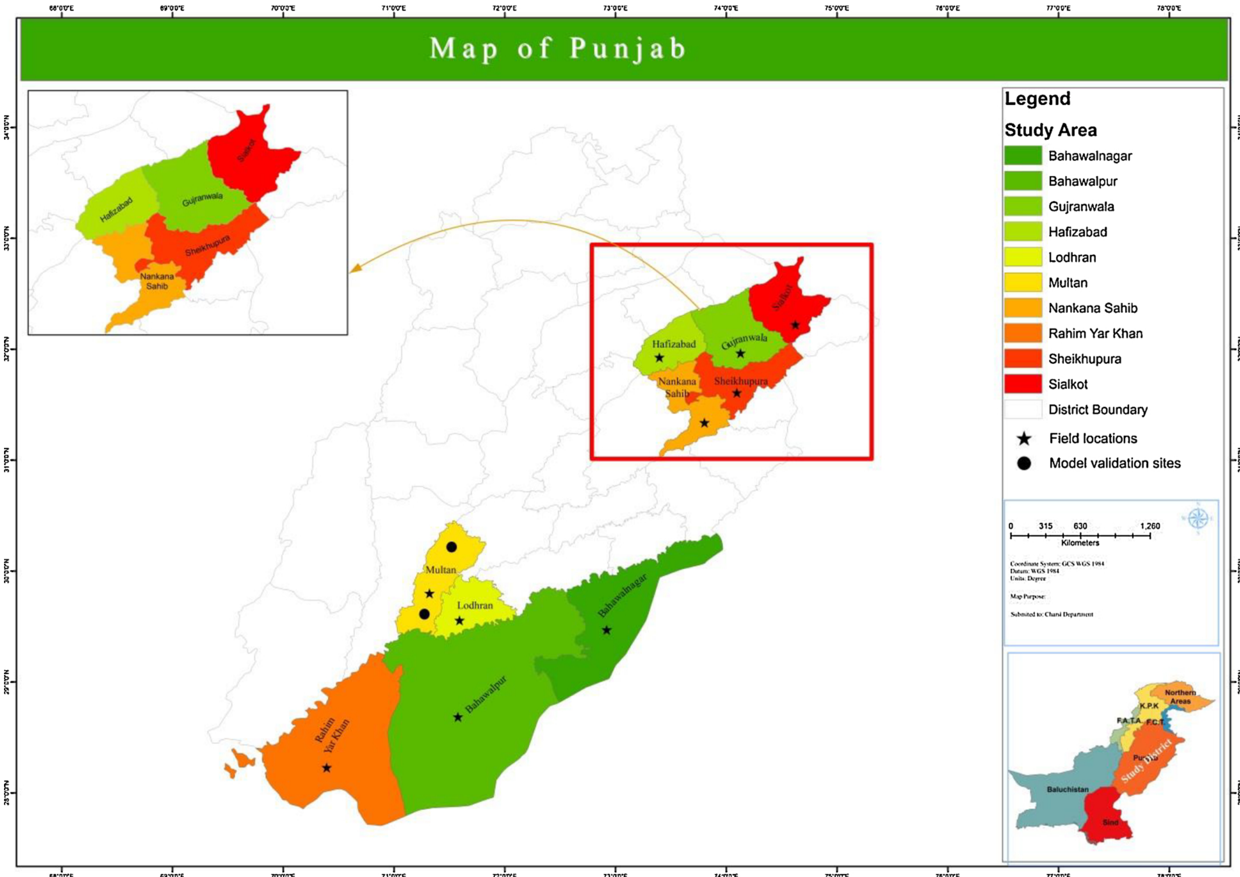

Fig. 1. Map showing districts, field locations, and experimental sites for model evaluation in Punjab, Pakistan.

Table 1
Rice and wheat cultivars grown at different locations of Punjab, Pakistan.

Locations	Coordinates	Cultivars
Rice		
Sialkot	32.49 °N; 74.53 °E	Basmati-370, IRRI-6, (KS-282[a]; 1982), KSK-414, Supra
Gujranwala	31.42 °N; 73.08 °E	(Basmati Pak[a]; 1968), IRRI-9, KSK-301, KSK-409, PK-3717-12
Hafizabad	32.07 °N; 73.69 °E	(Basmati-198[a]; 1972), IRRI-184, PARC-97, PK-578-20
Sheikhupura	31.72 °N; 73.98 °E	(Basmati-385[a]; 1985), Super fine, (KSK-133; 2006), PARC-154
Nankana Sahib	31.45 °N; 73.70 °E	Basmati-515, IRRI-8, KSK-412, (NIAB IRRI-9; 1999[a]), PK-939-4
Multan	30.19 °N; 71.47 °E	Basmati-386[a], IRRI-2053, KSK-411, KSK-133, PK-178-2
Lodhran	29.54 °N; 71.63 °E	(Super Basmati; 1996), IRRI-72[a], KSK-407, PK-3849-18
Bahawalpur	29.39 °N; 71.68 °E	(Basmati-2000; 2000), IRRI-74[a], KSK-420, Kashmira Taisen, Yu-255
Bahawalnagar	29.99 °N; 73.25 °E	(Shaheen Basmati; 2000), IRRI-GP-2, KSK-419[a], Malta, PK-1399
Rahim Yar Khan	28.42 °N; 70.29 °E	Rachna Basmati, IRRI-GP-275, KSK-418[a], Hero, PK-3699
Wheat	Elevations	
Sialkot	256 m	Punjab-76[a], Shafaq-2006, Chakwal-97, NIA Sarrang, LU-60, Shalimar-88
Gujranwala	226 m	Chenab-70, Uqaab-2000, Bhakar-2002, Benazir, LU-61, Pavon, Zamindar-80[a]
Hafizabad	207 m	Farid-2006, Inqalab-91, Hamal Faqir, LU-31, Faisalabad-85, Lyallpur-73[a]
Sheikhupura	236 m	SA-42[a], Pasban-90, Ufq-02, Dharabi-11, Pak-2013, Parwaz-97, Kohenoor-85
Nankana Sahib	187 m	SA-75, Manthar-03, Panjanand-1, Shehkar-2013, ARRI-10, SA-75, Punjab-81[a]
Multan	122 m	LU-26, PAK-81[a], Sehar-2006, Lasani-2008, AAS-2011, C-250, Faisalabad-85
Lodhran	112 m	LU-71, Faisalabad-83, GA-2002, AS-2002, Galaxy-2013, Punjnad-88, Sandal[a]
Bahawalpur	461 m	Mairaj-2008, Punjab-85, Wafaq-2001, Millat-2011, Pak-2013, C-271, BWP-79[a]
Bahawalnagar	163 m	Faisalabad-2008, Saleem-2000, NARC-2011, BARS-09, Pasban-90, Barani-83[a]
Rahim Yar Khan	81 m	Kohistan-97, NARC-2009, Sunehri-2010 Chakwal-50, Rohtas-90, C-275[a]

[a] Indicates cultivars used for model calibration; Years = Indicates years for release of cultivars; Source: Government of Punjab, Pakistan.

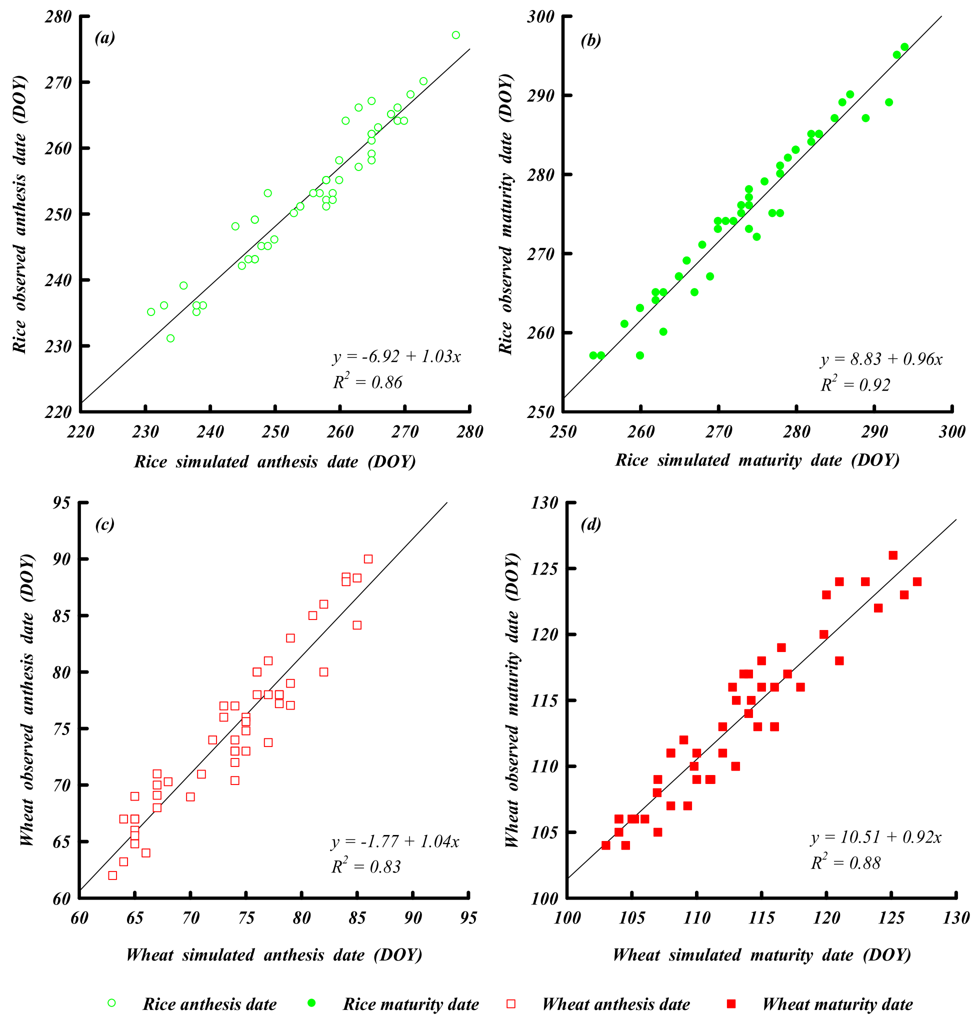

Fig. 2. Comparison of observed and simulated anthesis and maturity dates, respectively for rice (a, b) and wheat (c, d) during 1980–1985 at 10 locations under rice-wheat system in Punjab, Pakistan.

and is important for adaptation of individual crops and cropping systems to environmental vagaries (Ahmed et al., 2016; Hu et al., 2005; Menzel et al., 2006; Moriondo and Bindi, 2007; Madan et al., 2012; Mueller et al., 2014; Liu et al., 2018). The environmental conditions, thermal time requirements, and crop management practices (cultivar features and transplanting/sowing dates) have a significant effect on crop phenological stages and phases (Gordo and Sanz, 2005; Sadras and Monzon, 2006; Tao et al., 2006; Craufurd and Wheeler, 2009; Kariyeva et al., 2012; Rani and Maragatham, 2013; Zhang and Tao, 2013; Ahmad et al., 2017a, b; Abbas et al., 2017; Liu et al., 2018). Matching optimum levels of weather components such as temperature and rainfall at or during critical crop growth stages is crucial for the maximum expression of the genetic potential of various cropping systems (Peng et al., 2004; Visser and Both, 2005; Cleland et al., 2007; Jagadish et al., 2008; Amin et al., 2018). With climate warming, changes in crop phenological stages and phases are reducing crop growth and development cycles and decreasing the time and rate for biomass accumulation (Saseendran et al., 2000; Bindi and Moriondo, 2005; Guhey et al., 2009; van Oort et al., 2011v; Tao et al., 2013; Figueiredo et al., 2015; Abbas et al., 2017).

A better understanding of the response of crop phenological stages and phases to changing temperatures would improve agronomic management practices and crop breeding to mitigate the effects of climate change (Abbas et al., 2017; Ahmad et al., 2015; Hoffmann and Sgro, 2011). Hu et al. (2005) reported that advancement in anthesis dates of winter wheat has occurred during the previous seven decades in the US Great Plains due to rising spring temperatures. As a result, less time is available for the interception of light and total dry matter accumulation. He et al. (2015) reported that S and E dates were delayed by an average 1.2 and 1.3 days decade^{-1} and A, M, S-M and S-A were advanced by an average, 3.7, 3.1, 4.3, and 5.0 days decade^{-1}, respectively, in the Loess Plateau of China. Wheat phenological stages and A and M dates were about 2.7 and 1.4 days earlier decade^{-1} due to climate warming during the period of 1981 to 2009 in areas of North China (Xiao et al., 2013). Climate warming caused the advancement in the growth and development of wheat by an average of

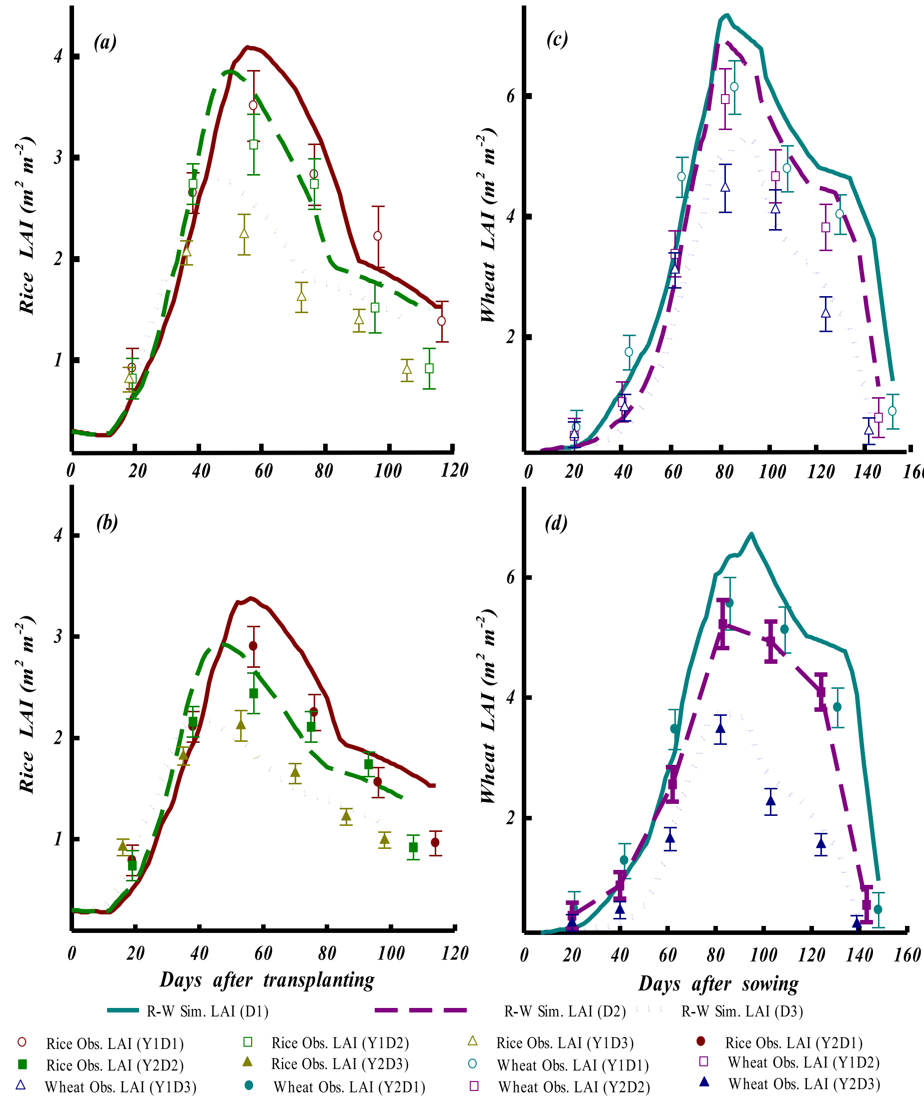

Fig. 3. Observed and simulated rice (a, b) and wheat (c, d) leaf area index (LAI) as affected by transplanting/sowing dates used for CERES-Rice and CERES-Wheat models evaluation during year-I (a, c) and year-II (b, d) field experiments under irrigated arid environment at Multan, Pakistan.

13.2 (stem elongation), 9.8 (booting), 11.0 (flowering), and 10.8 (physiological maturity) days decade^{-1} during the period of 1983 to 2004 in areas of the Loess Plateau of China (Wang et al., 2008). Crop growth and development could be accelerated due to the thermal warming trend, and negative effects of warming could be minimized by sowing crops later and by introducing new cultivars with high thermal time requirements (Asseng et al., 2011; Li et al., 2014; Rezaei et al., 2015). Regular adjustments in sowing/transplanting times and planting new crop cultivars have complicated the detection of crop phenology responses to thermal trends (Chmielewski et al., 2004; Menzel et al., 2006; Estrella et al., 2007; Li et al., 2016). The relationship between environmental variability, agronomic management practices, and changes in cultivars cannot be obtained by statistical models. However, this interaction can be simulated with process-based crop growth models such as DSSAT and APSIM (Hoogenboom et al., 2017; Jones et al., 2003; Keating et al., 2003; Ahmed et al., 2014; Zhao et al., 2014; He et al., 2015; Ahmad et al., 2016, 2017a,b; Abbas et al., 2017; Tariq et al., 2018). The impact of a single factor can be isolated from other factors (Liu et al., 2012; Wang et al., 2013; Abbas et al., 2017). The DSSAT crop simulation model can be used to isolate the effects of climate warming, crop management and cultivar changes on phenology of rice and wheat system. The goal of this study is to quantify the spatiotemporal variability of rice and wheat system phenology using historical data from 1980 to 2014. Specific objectives are to determine correlations among thermal trends, rice and wheat system phenology, management practices, and cultivar change and to investigate how climate warming has affected rice and wheat system phenological stages and phases.

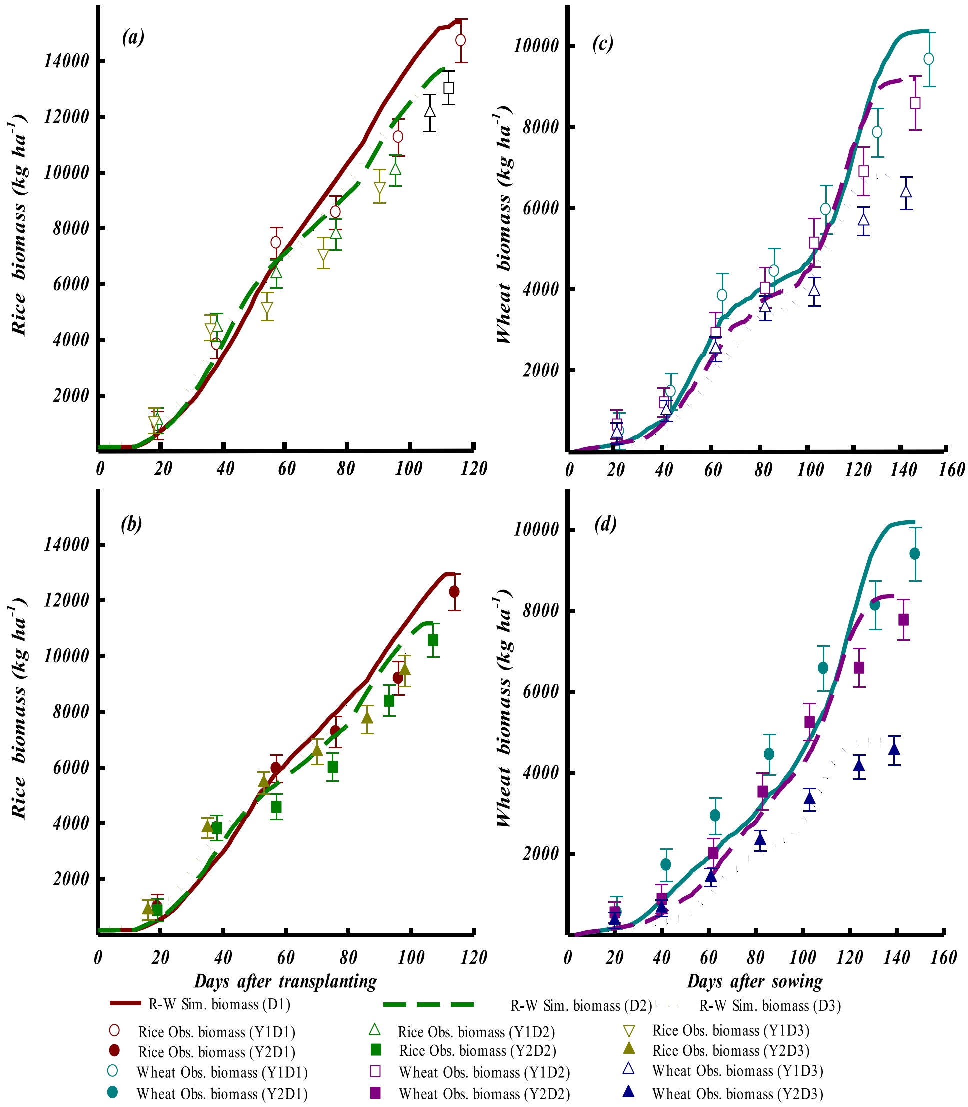

Fig. 4. Observed and simulated rice (a, b) and wheat (c, d) biomass as affected by transplanting/sowing dates used for CERES-Rice and CERES-Wheat models evaluation during year-I (a, c) and year-II (b, d) field experiments under irrigated arid environment at Multan, Pakistan.

2. Materials and methods

2.1. Description of locations, weather and rice-wheat phenology data

Rice-wheat is the cereal-based, staple cropping system most commonly adopted by farmers in the Punjab, Pakistan. The rice and wheat crops area and production from 1980 to 2014 in the Punjab province (a and b) and Pakistan (c and d), respectively, are presented in Fig. S1. In this system, commonly referred to as RWS, rice and wheat crops are sown during the summer and winter seasons, respectively, under irrigated conditions. For the present study, ten locations were selected (Fig. 1). The physical-chemical properties of the selected locations, coordinates, and height above sea level are presented in Table S1 (Supplementary files) and Table 1. The first five locations were research sites from the Agricultural Modeling Intercomparison and Improvement Project (AgMIP; Phase I) and the second five were sites of the Higher Education Commission (HEC) project (Supplementary files as SDF-1). Analysis of recent historical weather data of these districts shows an increase in minimum temperatures and maximum temperatures and a large variation in rainfall (Bokhari et al., 2017). Field experiments using RWS were conducted at two agronomic research areas from 2011 to 2013 for evaluation of CSM-CERES-Rice and CSM-CERES-Wheat models (Table S2). For the rice experiments, the treatments included four cultivars (Basmati-370, Basmati-385, Basmati-Pak, and Basmati-2000) and three transplanting dates (July 11th, 21st and 31st). For the wheat experiments, the treatments included four cultivars (ASS, AARI, Punjab and Millat) and three sowing dates (November 10th, 20th and 30th). Other management practices for RWS were kept standard as described in Table S3. Daily weather data from 1980 to 2014 were obtained from the Pakistan Meteorological Department (PMD) and were recorded at

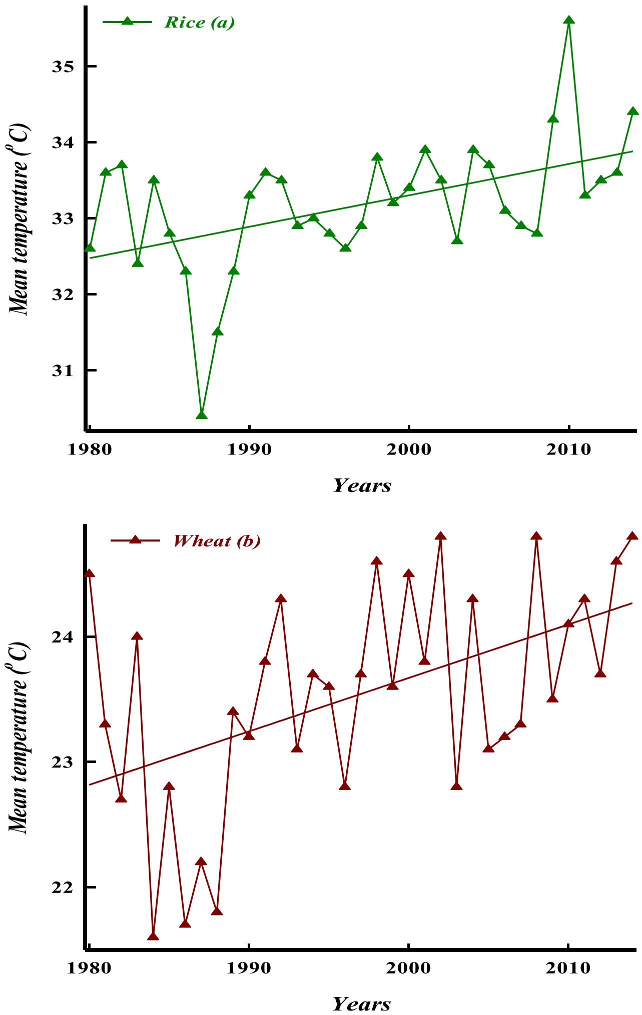

Fig. 5. Mean temperature trends during rice (a) and wheat (b) seasons under RWS from 1980 to 2014 in Punjab, Pakistan.

the observatories located in the study areas. The weather data included maximum and minimum temperature, rainfall, and solar radiation. Rice and wheat phenological data were obtained from the Extension Wing of the Department of Agriculture, Government of Punjab, Pakistan, for these locations from 1980 to 2014. The data on sowing (S), transplanting (T), panicle initiation (PI), anthesis (A), and maturity (M) dates were collected as rice phenology stages. Four phenological phases of rice crop, which included sowing to transplanting (S-T), transplanting to maturity (T-M), transplanting to panicle initiation (T-PI), panicle initiation to anthesis (PI-A), and anthesis to maturity (A-M), were calculated from the phenological stages data. For wheat phenology stages, data were collected on sowing (S), emergence (E), anthesis (A), and maturity (M) dates from which three phenological phases, sowing to anthesis (S-A), sowing to maturity (S-M), and anthesis to maturity (A-M), were calculated. Rice and wheat management practices were obtained from farmers in the study areas. Approximately every six to eight years farmers changed an average of five new rice cultivars per location, and every seven to nine years they changed an average of six wheat cultivars per location. These changes could alter respective crop temperature and growing degree days requirements. The names of rice and wheat cultivars are listed in Table 1.

2.2. Data analysis

Linear trends in observed RWS phenological data and respective average temperature were determined using simple linear regression, multiple linear regression, and "*t*-test", in which the year was the independent variable. To estimate temperature trends, growth periods were calculated from RWS by the longest phenology stage at each location. For example, the season lengths of RWS from earlier transplanting/sowing dates to the latest physiological maturity dates for the last decade at every location were used. By keeping the RWS growth duration constant, the temperature trend was free of particular phenology changes. Correlations of sowing/transplanting dates were determined with monthly average temperature for the respective month of sowing/transplanting to evaluate whether or not sowing/transplanting dates were motivated by temperature. The influence of temperature on RWS phenology was estimated using the following equation:

$$y_{nt} = \alpha + \beta_1 T_{nt} + \beta_2 M_{nt} + \varepsilon_{nt} \tag{1}$$

where 'y_{nt}' represents the observed phenology phases (days) or phenology stage day of year (DOY) of the respective n^{th} location in year t for both RWS. The $\beta_1 T_{nt}$ is the phenological coefficient that is influenced by temperature (days $^{\circ}C^{-1}$) of the n^{th}, location, $\beta_2 M_{nt}$ is the phenological coefficient influenced by management changes, while the 'α' is the intercept (the intercept indicate the value of 'y' when values of all 'x's' are zeroes). The '$\in_{nt}$' is the error term of every location. The phenological response of RWS to temperature and management changes is represented by the coefficient of regression.

2.3. Phenology simulation with CSM-CERES-Rice and CSM-CERES-Wheat models and thermal time estimation

The Decision Support System for Agrotechnology Transfer (DSSAT v. 4.7) was used for this study (Jones et al., 2003; Hoogenboom et al., 2017). In the CSM-CERES-Rice and CSM-CERES-Wheat models, RWS phenology is estimated through thermal time accumulation (degree days). Thermal time requirements of specific cultivars of RWS at each phenological stage are also determined by these models. The cumulative thermal time requirement from S/T – A and from A - M is determined as:

$$ATT = \left(\frac{Tmax + Tmin}{2}\right) - Tbase \tag{2}$$

where 'ATT' is the thermal time day^{-1} and 'n' represents the number of days of phenology for both RWS. Total growing degree days (GDD) for rice and wheat crops phenological phases, transplanting/sowing-anthesis (T/S-A), and anthesis-maturity (A-M) were computed for each 24-hour period from daily maximum (Tmax) and minimum (Tmin) air temperature measured hourly in degrees Celsius (°C) at a height of about 2 m according to Islam and Sikder (2011) and Aslam et al. (2017) by using the previous equation that calculates growing degree days as a function of mean temperature above a base temperature. Tbase for rice was 10 °C and for wheat was 4.5 °C (Islam and Sikder, 2011; Islam et al. 2017). A brief explanation of CSM-CERES-Rice and CSM-CERES-Wheat models is given in Table S4 (Supplementary files) and detailed information can be found at the DSSAT Portal (http://www.dssat.net).

Simulation results of crop phenology were obtained for a single

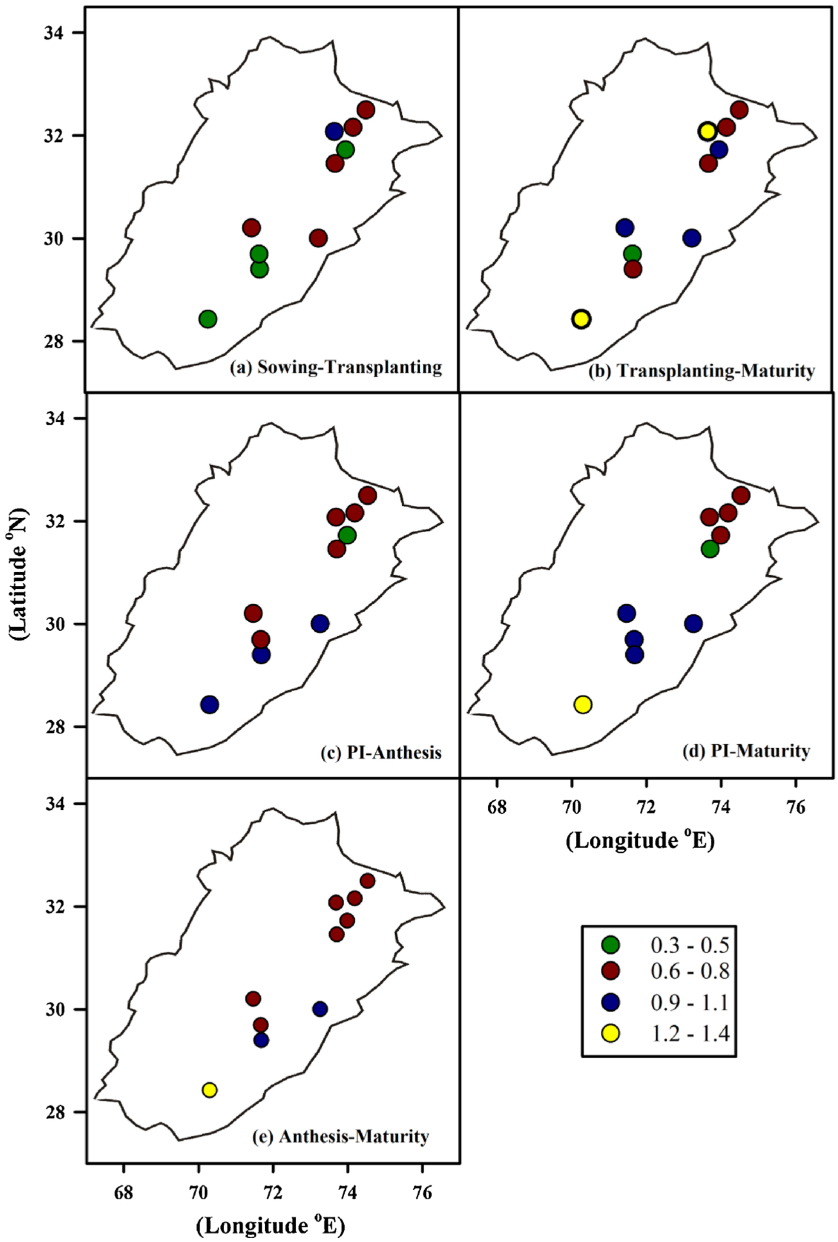

Fig. 6. Observed trends in mean temperature (ºC decade^{-1}) during the phenological phases of rice in Punjab, Pakistan from 1980 to 2014, (a) transplanting-maturity; (b) panicle initiation-anthesis; (c) panicle initiation-maturity; (d) anthesis-maturity.

cultivar of each crop. The same crop management file was used for all years to isolate the effect of cultivar, crop management, and temperature on RWS phenological stages and phases. Sowing, transplanting, panicle initiation, anthesis, maturity dates, and total season length for rice, as well as sowing, emergence, anthesis, and maturity dates for wheat were predicted from 1980 to 2014 for all ten locations in the Punjab, Pakistan. The CSM-CERES-Rice and CSM-CERES-Wheat models were calibrated using the primary cultivar for rice or wheat planted for each location from 1980 to 1982. Once calibrated, evaluation of these models was conducted using observed phenological data from 1983 to 1985. The two crop models were then used to simulate RWS phenology from 1980 to 2014 by applying the same management practices at each location. The correlations of simulated crop phenology to temperature were estimated as:

$$SP_{nt} = C_{nt}T_{nt} + d_{nt} + \varepsilon_{nt} \tag{3}$$

where 'SP_{nt}' is the predicted phenology length in days of the n^{th} location during year t for each crop. 'T_{nt}' is the mean temperature (ºC) during phases of RWS phenology of the n^{th} location in year t. C_{nt} is the slope of the linear regression of RWS phenology that responds to the temperature (days ºC^{-1}) of the n^{th} location. d_{nt} is the intercept and $\in_{nt}$ is the error term. The relationship between observed and simulated anthesis

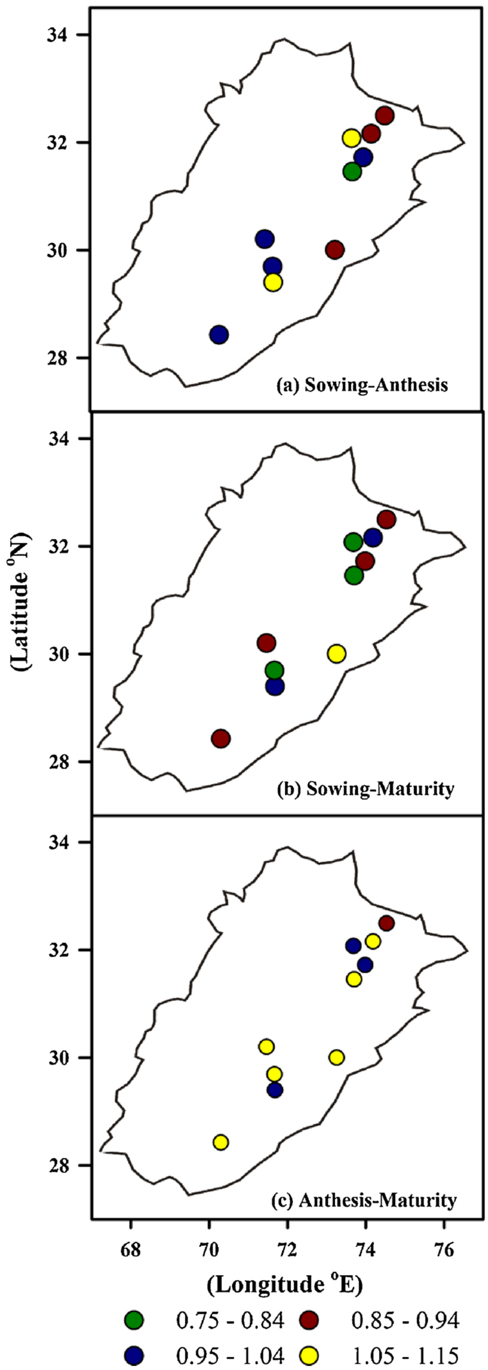

Fig. 7. Observed trends in mean temperature (ºC decade^{-1}) during the phenological phases of wheat in Punjab, Pakistan from 1980 to 2014, (a) sowing-anthesis; (b) sowing-maturity; (c) anthesis-maturity.

and physiological maturity dates of the evaluation period (1980–1985) at the studied locations is shown in Fig. 2(a–d) for both crops. There was a good agreement between observed and simulated anthesis dates (slope = 1.03, R^2 = 0.86, p < 0.01) and maturity dates (slope = 0.96, R^2 = 0.92, p < 0.01) for rice crop (Fig. 2(a) and (b), along with similar response for wheat crop showing trends between observed and simulated anthesis dates (slope = 1.04, R^2 = 0.83, p < 0.01) and maturity dates (slope = 0.92, R^2 = 0.88, p < 0.01) (Fig. 2(c) and (d) suggesting that CSM-CERES-Rice and CSM-CERES-Wheat models performed well for the study area. Seasonal patterns of observed and simulated leaf area index (LAI) and above-ground biomass of RWS crops as affected by transplanting/sowing dates for both the years (from 2011 to 2013) used for evaluation of the CSM-CERES-Rice and CSM-CERES-Wheat models are presented in Figs. 3 and 4.

2.4. *Observed response vs simulated response to temperature*

Rice and wheat phenological response to temperature, sowing/transplanting dates, and change of cultivar are reflected by variable 'a_{nt}', which is the regression coefficient in Eq. (1). Only the temperature effect is reflected by c_{nt}, the regression coefficient in Eq. (3). If the difference between regression coefficients (a_{nt}–C_{nt}) is positive, then during the previous decades farmers adopted those cultivars that had long growing seasons; if the difference was negative, then farmers adopted those cultivars that had short growing seasons. In our study, increasing temperature influence on observed phenology of RWS was ameliorated 35% [= (0.47/1.55 + 0.59/1.75 + 0.32/1.05 + 0.48/1.79 + 0.55/1.01)/5], Table 4] on rice and 21% [= (0.48/2.07 + 0.29/2.38 + 0.74/2.55)/3, Table 4] on wheat due to the introduction of new cultivars for RWS (He et al., 2015; Xiao et al., 2016). The Paired *t*-test was used to test the differences in regression coefficient for every crop and stage (He et al., 2015; Ahmad et al., 2016, 2017a,b; Abbas et al., 2017; Tariq et al., 2018; Liu et al., 2018).

3. Results

3.1. *Temperature trends in RWS*

Climate warming was observed in phenological phases of rice from 1980 to 2014 for all ten study locations (Figs. 5(a) and 6). The rate of warming ranged from 0.30 to 0.90 °C decade^{-1} for S-T and 0.50 to 1.20 °C decade^{-1} for T-M, while for PI-A, PI-M, and A-M, it varied from 0.40 to 0.90, 0.40 to 1.20, and 0.60 to 1.20 °C decade^{-1}, respectively. Analogous ranges for climate warming rates for wheat were 0.78 to 1.10, 0.77 to 1.07, and 0.93 to 1.10 ºC decade^{-1} for S-A, S-M, and A-M (Figs. 5(b) and 7). Mean values for these corresponding phases were 0.96 (S-A), 0.91 (S-M), and 1.04 (A-M) ºC decade^{-1}.

3.2. *Spatial and temporal variations in RWS phenological stages*

The rice nursery in the Punjab, Pakistan, is usually grown from late May to mid–June, and transplanted from the middle to the end of June (Table S5). The impact of climate warming on rice phenology showed that the most and least affected locations were Multan and Bahawalpur, respectively, as rice reached A and M stages early with minimum and maximum days (Fig. 8). Rice A and M dates occurred earlier with delayed transplanting and sowing dates (Table S5). The spatial trends and temporal variability of rice phenology stages are presented in Table S5. From 1980 to 2014 in Punjab, Pakistan, sowing was advanced significantly (p < 0.05) at seven locations, T advanced significantly (p < 0.05) at nine locations), and PI advanced significantly (p < 0.05) at six locations by about 6.90 to 9.10 days decade^{-1}, 5.40 to 7.70 days decade^{-1} and 1.90 to 5.70 days decade^{-1}, respectively. Anthesis and maturity of rice usually occurred from late July to early August and from mid-September to mid-October. Anthesis dates were earlier and

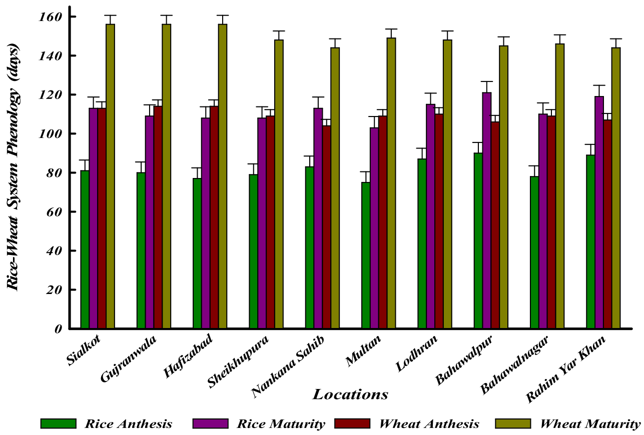

Fig. 8. Impact of climate warming on rice-wheat system phenology (mean days to anthesis and maturity from transplanting/sowing) at ten locations during the period of.1980–2014.

significant ($p < 0.05$) at seven locations, while maturity was significantly earlier ($p < 0.05$) at eight locations. The range of earliness varied between 2.60 to 6.30 days decade^{-1} and 5.00 to 7.90 days decade^{-1}. Time series plots of farmer field observed dates of sowing, transplanting, panicle initiation, anthesis and maturity of rice in Punjab, Pakistan location-wise are presented in Fig. 9.

Normally, wheat is sown from early November to mid-December in Punjab, Pakistan (Table 2). The climate warming impact on wheat phenology showed that the most affected location was Nankana Sahib and the least affected location was Hafizabad, as wheat took minimum and maximum days for anthesis and maturity (Fig. 8). Wheat anthesis and maturity dates approached early with delay in sowing (Table S5). Table S5 shows the temporal and spatial trends of wheat planting dates. Sowing dates of wheat were delayed from 1980 to 2014 for all locations. The observed average delay in sowing was significant ($p < 0.05$) at eight locations and emergence dates were delayed significantly ($p < 0.05$) at seven locations. The average delays of wheat sowing and emergence dates for all locations was 9.50 days decade^{-1} and 1.30 days decade^{-1}). Anthesis of wheat in Punjab, Pakistan normally occurs from mid-February to early March. Anthesis was significantly earlier ($p < 0.05$) for eight locations and maturity dates were significantly earlier ($p < 0.05$) for seven locations. Across all locations, anthesis and maturity dates were earlier with an average of 5.20 and 5.30 days decade^{-1}, respectively. Time series plots of farmer field observed dates of sowing, emergence, anthesis and maturity of wheat in Punjab, Pakistan location-wise are presented in Fig. 10.

3.3. Spatial and temporal variations in RWS phenological phases

The S-T, T-M, PI-A, PI-M phases of rice decreased significantly ($p < 0.05$) at eight locations, and A-M decreased significantly ($p < 0.05$) at seven locations. These phases decreased for all locations on average of 1.40, 6.40, 3.00, 4.70, and 4.10 days decade^{-1}, respectively (Table S6). The effect of the climate warming trend on wheat phenological phases is presented in Table S6. The decrease in wheat S-M ranged from 4.80 to 7.20 days decade^{-1} and was significant ($p < 0.05$) for nine locations. The decrease in S-A was significant ($p < 0.05$) for eight locations and ranged from 4.40 to 7.00 days decade^{-1}. The decrease in A-M was significant ($p < 0.05$) for all ten locations and duration ranged from 3.20 to 6.50 days decade^{-1}. These changes were due to a delay in sowing and early maturity.

3.4. Spatial and temporal variations in RWS cultivar's thermal response

The thermal requirement of rice cultivars for S-T was significant ($p < 0.05$) for four locations, T-A was significant ($p < 0.05$ for five locations, and A-M was significant ($p < 0.05$) for four locations. The development phases S-T, T-A, and A-M increased, ranging between 31 to 68 ºC d decade^{-1}, 37 to 96 °C d decade^{-1} and 47 to 79 °C d decade^{-1} across all locations, respectively (Table S7). Wheat thermal time requirement from S-A increased significantly ($p < 0.05$) for six locations and A-M increased significantly ($p < 0.05$) for eight locations. These phases increased for all locations by an average of 82 ºC d decade^{-1} and 75 °C d decade^{-1}, respectively (Table S7).

3.5. Response of observed phenology of RWS to temperature

The interactive effect of climate warming and crop management practices on rice phenology is presented in Fig. 11(a, b). Multan was the most affected location and Bahawalpur and Rahim Yar Khan were the least affected locations. There was a negative correlation of sowing dates significant ($p < 0.05$) for four locations and transplanting dates significant ($p < 0.05$) for four locations with temperature for all ten locations, with regression coefficient values ranging from −1.72 to −2.60 –and −0.54 to −2.51 days ºC^{-1}, respectively (Table 3; Fig. 12). Negative and positive correlations of PI dates, significant ($p < 0.05$) for two locations with temperature were observed for eight and two locations and regression coefficients varied from −1.65 to 3.08 days ºC^{-1}. Anthesis was earlier but non-significant ($p > 0.05$) for nine locations and maturity dates occurred earlier and were significant ($p < 0.05$) for two locations. The regression coefficients ranged from -0.29 to −2.63 days ºC^{-1} and −0.13 to −3.39 days ºC^{-1} for anthesis and maturity, respectively. The S-T phase significant ($p < 0.05$) for five locations and T-M phase significant ($p < 0.05$) for two locations, were negatively correlated with temperature, and the values for regression coefficient ranged from −0.52 to −1.95 and −0.9 to −3.39 days ºC^{-1}, respectively (Fig. 11). For most of the locations, there was a negative correlation of PI-A, significant ($p < 0.05$) for four locations, and PI-M phases significant ($p < 0.05$) for five locations with temperature. The regression coefficients ranged between −0.05 to −2.52 days ºC^{-1} and −0.18 to −2.83 days ºC^{-1}, respectively. There was only one location that had a positive correlation with a value of 0.29 days ºC^{-1}. The A-M phase significant ($p < 0.05$) for two locations was advanced at most locations along with a negative correlation was observed with temperature and regression coefficient values ranged from -0.13 to -1.54 days ºC^{-1}. A positive correlation of A-M phase and temperature was observed for only one location with a regression coefficient of 1.31 days ºC^{-1}.

The interactive effect of climate warming and crop management practices on wheat phenology is presented in Fig. 11(c, d). Nankana Sahib was the most affected and Hafizabad was the least affected location. The regression coefficient of observed phenological stages and phases with temperature is presented in Table 3 and Fig. 13. Positive correlations of sowing dates, which were significant ($p < 0.05$) for eight locations and emergence dates, which were significant ($p < 0.05$) for seven locations, were obtained with temperature for all ten locations with an average regression coefficient of 3.01 and 0.55 days ºC^{-1}. The correlations of anthesis, significant ($p < 0.05$) for eight locations and maturity dates, significant ($p < 0.05$) for seven

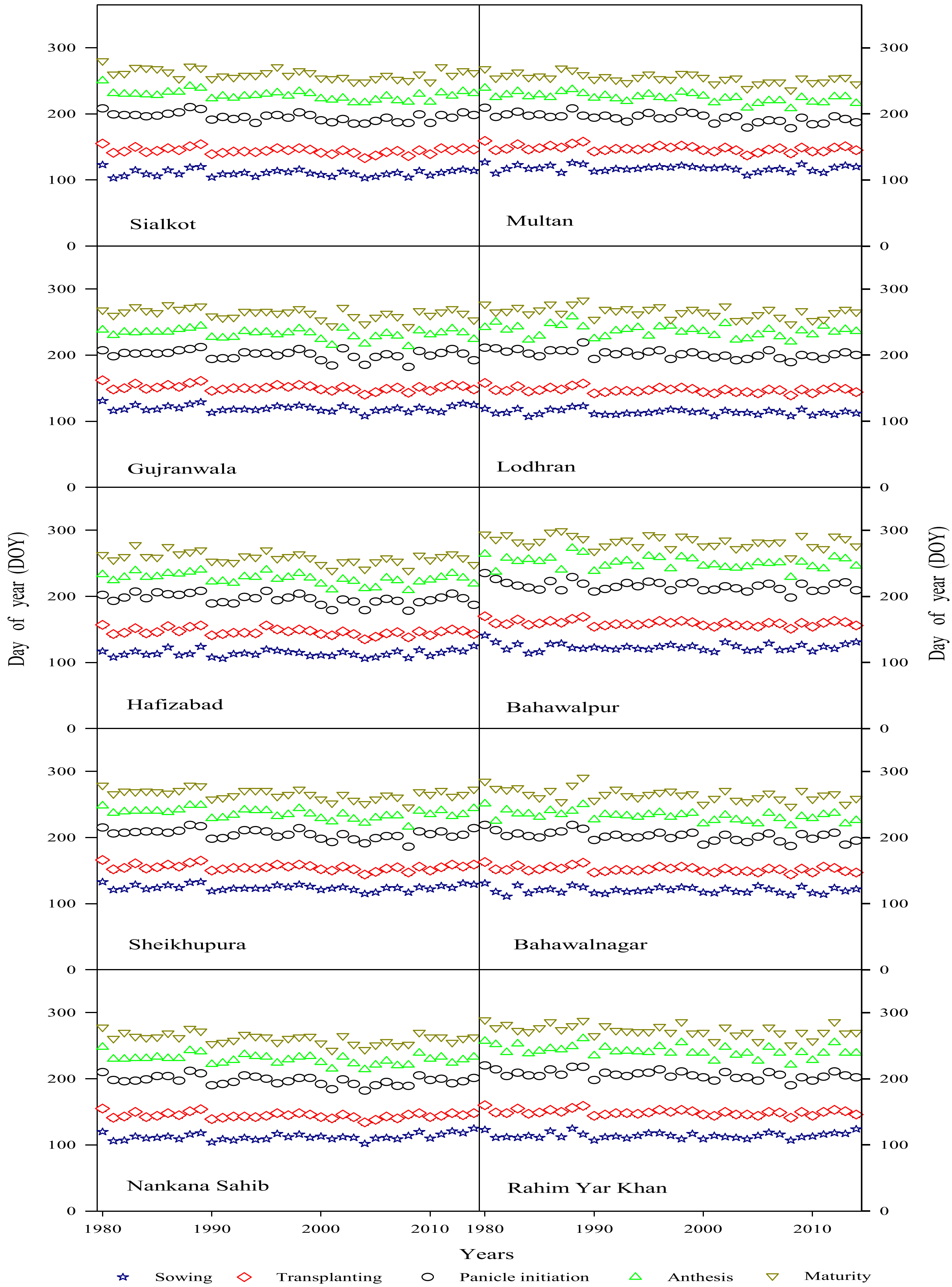

Fig. 9. Time series plots of farmer field observed dates of sowing, transplanting, panicle initiation, anthesis and maturity of rice in Punjab, Pakistan.

Table 2
Average observed phenology of rice and wheat crops (day of year) in Punjab, Pakistan during the period of 1980–2014.

Locations	Sowing	Transplanting	Panicle[a] Initiation	Anthesis[b]	Maturity[c]
Rice					
Sialkot	115 ± 4.8	141 ± 6.0	190 ± 5.8	215 ± 6.3	278 ± 5.3
Gujranwala	122 ± 6.2	148 ± 7.1	185 ± 6.6	219 ± 5.3	287 ± 4.7
Hafizabad	113 ± 5.3	138 ± 4.2	192 ± 3.9	222 ± 4.4	280 ± 6.3
Sheikhupura	120 ± 4.9	146 ± 5.1	196 ± 4.8	228 ± 6.6	274 ± 4.2
Nankana Sahib	124 ± 7.1	150 ± 6.4	194 ± 6.1	223 ± 3.2	286 ± 5.4
Multan	118 ± 5.8	146 ± 5.9	198 ± 5.4	232 ± 3.9	293 ± 5.2
Lodhran	124 ± 3.2	153 ± 4.6	201 ± 4.2	226 ± 4.4	289 ± 6.0
Bahawalpur	121 ± 6.1	147 ± 5.2	205 ± 4.9	234 ± 5.8	298 ± 7.4
Bahawalnagar	121 ± 3.5	156 ± 3.4	199 ± 3.2	231 ± 4.9	302 ± 5.9
Rahim Yar Khan	127 ± 7.2	158 ± 6.2	208 ± 5.8	229 ± 6.8	296 ± 6.3

Locations	Sowing	Emergence	Anthesis[a]	Maturity[b]
Wheat				
Sialkot	316 ± 5.6	321 ± 5.2	65 ± 5.3	113 ± 6.4
Gujranwala	319 ± 4.9	324 ± 4.5	72 ± 6.1	118 ± 5.8
Hafizabad	314 ± 3.7	318 ± 3.4	78 ± 5.3	120 ± 4.1
Sheikhupura	326 ± 5.9	330 ± 5.3	70 ± 6.8	123 ± 5.9
Nankana Sahib	322 ± 6.2	326 ± 5.9	74 ± 7.4	122 ± 4.7
Multan	321 ± 5.1	325 ± 4.5	79 ± 4.9	118 ± 6.7
Lodhran	318 ± 6.4	323 ± 6.1	73 ± 6.2	126 ± 4.0
Bahawalpur	326 ± 4.8	330 ± 4.5	78 ± 4.4	122 ± 5.6
Bahawalnagar	324 ± 5.7	328 ± 5.2	80 ± 5.8	124 ± 5.2
Rahim Yar Khan	328 ± 5.3	332 ± 4.8	83 ± 6.4	127 ± 6.1

± Standard deviation.
[a] 50% Panicle initiation.
[b] 50% Anthesis.
[c] 50% Physiological maturity.

locations, with temperature were negative, and average values of regression coefficient were −1.97 and −2.77 days ºC^{-1}. The correlations of S-A, which were significant ($p < 0.05$) for eight locations, S-M, which were significant ($p < 0.05$) at nine locations, and A-M phases, which were significant ($p < 0.05$) at ten locations, with temperature were also negative, with an average regression coefficient of −1.59, −2.07, and −1.81 days ºC^{-1}, respectively.

3.6. Response of simulated RWS phenology to temperature

The correlation between CSM-CERES-Rice model simulated phenology phases and temperature was negative (Fig. 12). The S-T and T-M phases were significant ($p < 0.05$) for nine locations, PI-A, PI-M, and A-M phases were all significant ($p < 0.05$) for eight locations, and the regression coefficients ranged from 1.10 to 2.31, 0.63 to 3.49, 0.22 to 2.02, 0.49 to 3.04, and 0.38 to 1.44 days ºC^{-1}, respectively (Table 3). There was a negative correlation between the CSM-CERES-Wheat model predicted phenological phases and the thermal trend (Table 3 and Fig. 13). The S-A phase was significantly advanced ($p < 0.05$) for ten locations, A-M was significantly advanced ($p < 0.05$) for nine locations, and the S-M phase was significantly advanced ($p < 0.05$) for eight locations. The average regression coefficients were 2.07, 2.55, and 2.38 days °C^{-1}, respectively.

3.7. Observed vs simulated RWS phenology

Model-simulated RWS phenology was more sensitive than observed phenology (Table 4). The differences between predicted and observed RWS phenology were significant ($p < 0.05$). The response to changes between predicted and observed phenological phases with high temperature indicated that new rice and wheat cultivars that having a higher thermal time requirements were selected by farmers during the last decades.

4. Discussion

Increasing temperature during the last three decades was the most important factor that caused either a delay or advancement in observed RWS phenological development (Siebert and Ewert, 2012; Gouache et al., 2012; Oteros et al., 2015; Ahmad et al., 2016, 2017a,b; Abbas et al., 2017; Liu et al., 2018). The long-term increase in ambient temperature (~0.01 °C yr^{-1}) resulted in shifts in phenological development (Ellwood et al., 2012). Changes in frequency, intensity, and duration of extreme temperature events disrupt crop processes, predominantly reproduction (Rasul et al., 2012; Talukder et al., 2013; Amin et al., 2018). To some extent, changes in the nursery sowing and transplanting dates, for rice only, and growing new cultivars of rice and wheat with high thermal time requirements affected RWS phenology (Peng et al., 2004; Liu et al., 2012, 2018; Ahmad et al., 2015). Altering the sowing date is a good adaptation option to mitigate climate change impacts on crop production (Estrella et al., 2007; Ahmad et al., 2017a,b; Abbas et al., 2017). Generally, warming caused a delay in sowing dates (corresponding changes in phase's duration) in the study areas as an adaptation. The warming also caused advancement in the rice phenological stages such as PI, A, and M dates. As a result, the duration for T-PI, PI-A, PI-M, and A-M were reduced (Yao et al., 2007; Tao et al., 2013; Ahmad et al., 2015). Our results from the CSM-CERES-Rice model showed that simulated phenology varied widely, ranging from 215 to 234 days of year (DOY) for anthesis and 274 to 302 for maturity dates for all locations. Similarly, advances in wheat A and M

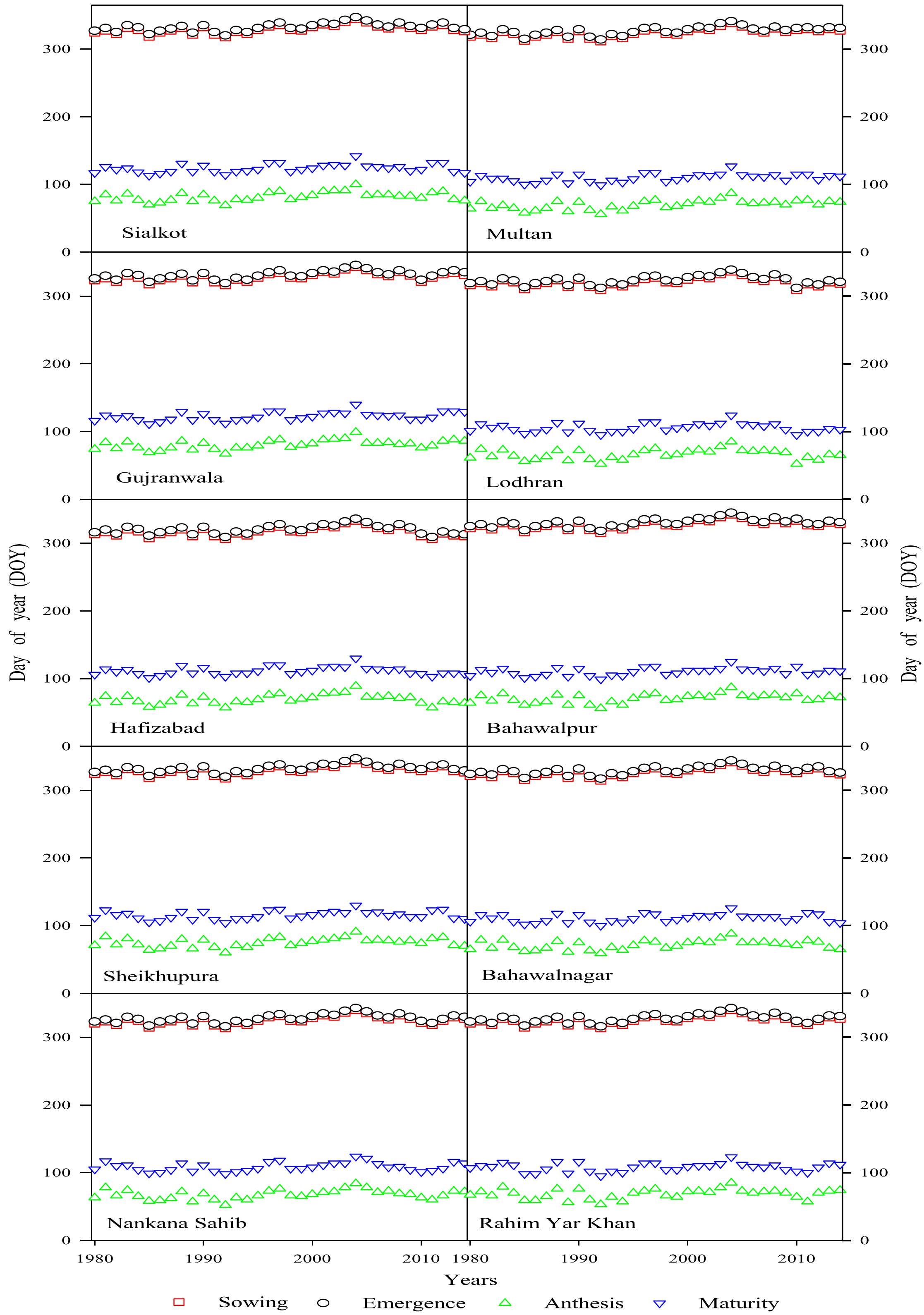

Fig. 10. Time series plots of farmer field observed dates of sowing, emergence, anthesis and maturity of wheat in Punjab, Pakistan.

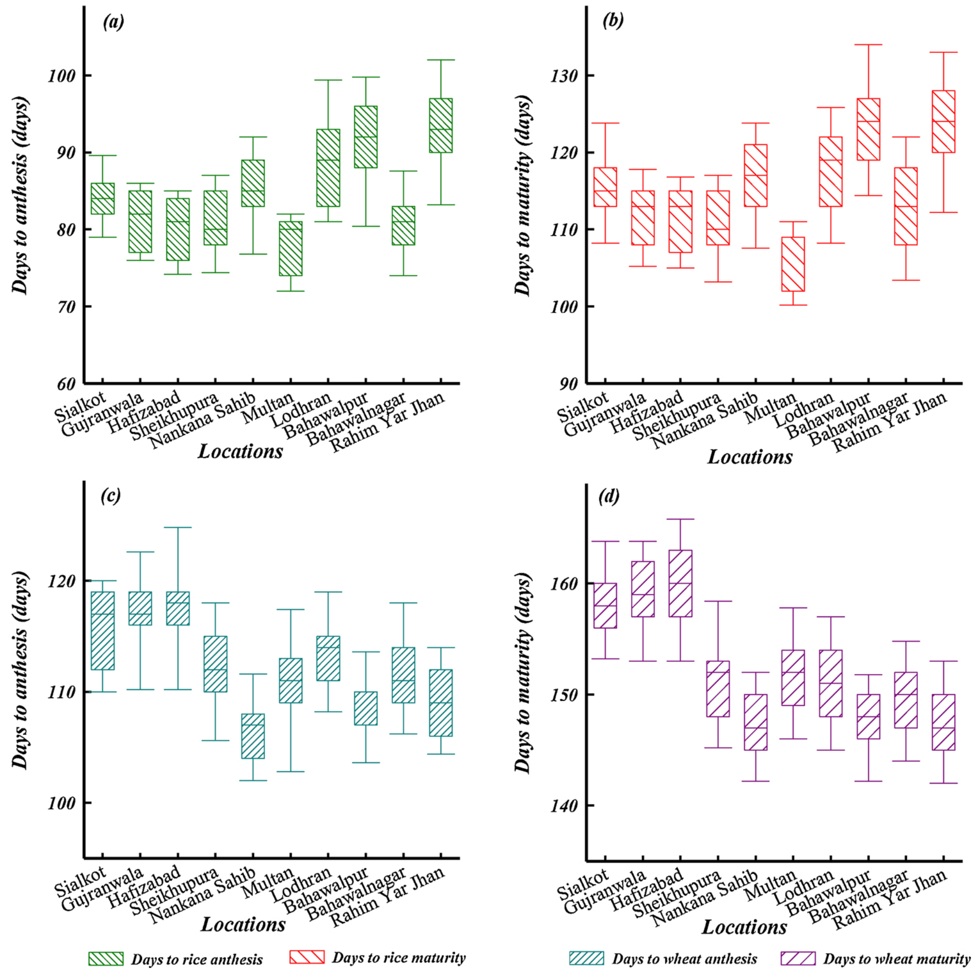

Fig. 11. Interactive effect of climate warming and crop management practices on phenology (days taken to anthesis and maturity from transplanting/sowing) of rice (a, b) and wheat (c, d) system at ten locations during period of 1980–2014. Box central line represents median; box lower and upper limits represent 25th and 75th percentiles; whiskers represent minimum and maximum values.

dates were due to warming and resulted in shortening of phenological phases like S-A, S-M, and A-M. Earliness in A and M dates due to climate warming has been observed for various cropping systems (Sparks et al., 2000; Abu-Asab et al., 2001; Fitter and Fitter, 2002; Ortiz et al., 2008; Lobell et al., 2012; Tao et al., 2012; Xiao et al., 2013; Zhang et al., 2013; He et al., 2015; Ahmad et al., 2012, 2013, 2017a,b; Abbas et al., 2017; Liu et al., 2018). Likewise, progression in A and M dates has been reported for other agricultural crops (Williams and Abberton, 2004; Sparks et al., 2005; Hu et al., 2005; Wang et al., 2008; Tao et al., 2014; Xiao et al., 2016; Ahmad et al., 2017a,b; Abbas et al., 2017). Different global circulation models (GCMs) predict that warming in Pakistan will increase more in the future than in the past (Amin et al., 2018; Bokhari et al., 2017). The mean temperature in the Punjab, Pakistan is expected to increase by almost 2–4 °C by the end of 21st century (Afzaal et al., 2009; Rasul et al., 2012; IPCC, 2014; Ahmad et al., 2015, 2016; Bokhari et al., 2017). Crop phenology may also be affected due to increasing soil temperature through its impacts on soil moisture, organic matter, soil drying and microbial activity (Linderholm, 2006). A decreasing trend in relative humidity (Neil and Wu, 2006) and increasing trend in wind speed and evapotranspiration (Brown et al., 2012) may also have a negative influence on crop phenology.

Adaptation options to climate change include development of new rice and wheat cultivars with modified phenological features that should be optimized according to the climatic conditions of a region (Brancourt-Hulmel et al., 2003; Liu et al., 2010; Zhang et al., 2013; Tao et al., 2013; Martín et al., 2014; Abbas et al., 2017; Liu et al., 2018). In our findings, simulated RWS phenological results were higher than the observed in response to climate warming, which suggested that the influence of the increase in temperature on observed phenology was ameliorated by 35% on rice and 21% (Table 4) on wheat due to the introduction of new rice and wheat cultivars (adopted from He et al., 2015; Xiao et al., 2016). A similar tendency to use new, better adapted cultivars in response to global warming was observed for wheat in the Loess Plateau of China (Liu et al., 2010; Xiao et al., 2013; He et al., 2015; Liu et al., 2018), in rice zones in China (Tao et al., 2013), for maize crops in China (Liu et al., 2013), in the maize belt of the USA (Sacks and Kucharik, 2011), and the maize-and sunflower-based cropping systems in Punjab, Pakistan (Abbas et al., 2017; Tariq et al., 2018).

The efforts of farmers of Punjab, Pakistan, to produce sufficient food for local consumption under the RWS is at risk because the productivity of the system is expected to decline under current and future climate scenarios (Ahmad et al., 2015). There was a clear indication of climate

Table 3
Summary of observed and simulated phenology response to temperature for rice and wheat in Punjab, Pakistan for 1980–2014.

Phenology	No. neg.[a]	No. pos.[b]	No. sig. neg.[c]	No. sig. pos.[d]	Reg. coefficients mean[e] (days °C^{-1})
Rice Observed Stages and Phases					
Sowing	10	0	7	0	−2.12
Transplanting	10	0	4	0	−1.56
Panicle initiation	8	2	1	1	−0.74
Anthesis	9	1	0	1	−0.80
Maturity	9	1	2	0	−1.16
Sowing-Transplanting	10	0	5	0	−1.08
Transplanting-Maturity	9	1	2	0	−1.2
Panicle initiation-Anthesis	9	1	4	0	−0.73
Panicle initiation-Maturity	9	1	5	0	−1.31
Anthesis-Maturity	9	1	2	0	−0.46
Rice Simulated Phases					
Sowing-Transplanting	10	0	9	0	−1.55
Transplanting-Maturity	10	0	9	0	−1.75
Panicle initiation-Anthesis	10	0	7	0	−1.05
Panicle initiation-Maturity	10	0	8	0	−1.79
Anthesis-Maturity	10	0	8	0	−1.01
Wheat Observed Stages and Phases					
Sowing	0	10	0	8	3.01
Emergence	0	10	0	7	0.55
Anthesis	10	0	8	0	−1.97
Maturity	10	0	7	0	−2.77
Sowing-Anthesis	10	0	8	0	−1.59
Sowing-Maturity	10	0	9	0	−2.09
Anthesis-Maturity	10	0	10	0	−1.81
Wheat Simulated Phases					
Sowing-Anthesis	10	0	10	0	−2.07
Sowing-Maturity	10	0	8	0	−2.38
Anthesis-Maturity	10	0	9	0	−2.55

[a] Number of locations with negative regression coefficients.
[b] Number of locations with positive regression coefficients.
[c] Number of locations with significant negative regression coefficients.
[d] Number of locations with significant positive regression coefficients.
[e] Mean of regression coefficients.

Table 4
Comparison of the responses of rice and wheat phenology with average temperature using the observed and simulated data in Punjab, Pakistan during 1980–2014.

Phenology	Regression coefficient (days ºC^{-1})		Difference between obs. and sim. data (days ºC^{-1})	*t*-Test (p-value)
	Obs. data	Sim. data		
Rice				
Sowing-Transplanting	−1.08	−1.55	−0.47	0.0029*
Transplanting-Maturity	−1.2	−1.75	0.55	0.0012**
Panicle initiation-Anthesis	−0.73	−1.05	0.32	0.018*
Panicle initiation-Maturity	−1.31	−1.79	0.48	0.0015**
Anthesis-Maturity	−0.46	−1.01	0.55	0.0018**
Wheat				
Sowing-Anthesis	−1.59	−2.07	0.48	0.0013**
Sowing-Maturity	−2.09	−2.38	0.29	0.0002**
Anthesis-Maturity	−1.81	−2.55	0.74	0.0009**

Obs. = Observed; Sim. = Simulated.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

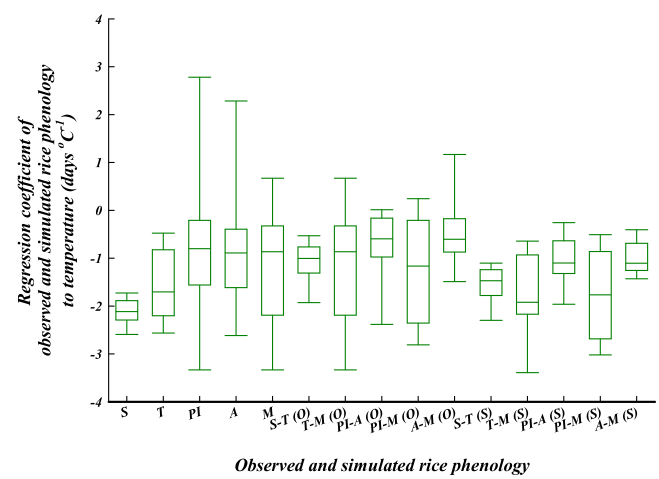

Fig. 12. Observed phenology (stages and phases) and simulated phenology (phases) versus temperature trends using a standard rice cultivar at each location in Punjab, Pakistan from 1980 to 2014. (S: sowing; T: transplanting; PI: panicle initiation; A: anthesis; M: maturity; S-T : sowing-transplanting; T-M: transplanting-maturity; PI-A: panicle initiation-anthesis; PI-M: panicle initiation-maturity; A-M : anthesis-maturity; O: observed; S: simulated). Box central line represents median; box lower and upper limits represent 25th and 75th percentiles; whiskers represent minimum and maximum values.

warming for all ten locations in this study, with an increase of 2–3 °C (Ahmad et al., 2016; Abbas et al., 2017; Bokhari et al., 2017). Therefore, in order to mitigate the negative impacts of climate change in Punjab, Pakistan, it is important to continuously develop and introduce new rice and wheat cultivars that have higher growing degree day requirements, temperature tolerance and high yield potential (Ahmad et al., 2017a,b; Abbas et al., 2017; Tariq et al., 2018).

5. Conclusions

A climate warming trend seriously affected the rice season by advancing the phenological stages and reducing the growth phases. However, wheat behaved differently during a climate warming trend, as S and E dates were delayed, while, A and M dates were advanced. The wheat phases were reduced at all the selected locations from 1980 to 2014. The negative impacts of warming on RWS phenology were partially mitigated through the introduction of new cultivars requiring a higher number of growing degree days.

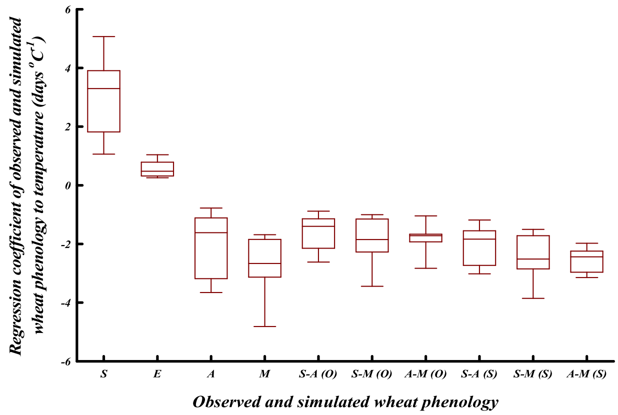

Fig. 13. Observed phenology (stages and phases) and simulated phenology (phases) versus temperature trends using a standard wheat cultivar at each location in Punjab, Pakistan from 1980 to 2014. (S: sowing; E: emergence; A: anthesis; M: maturity; S-A: sowing-anthesis; S-M: sowing-maturity; A-M : anthesis-maturity; O: observed; S = simulated). Box central line represents median; box lower and upper limits represent 25th and 75th percentiles; whiskers represent minimum and maximum values.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.10.008.

References

Abbas, G., Ahmad, S., Ahmad, A., Nasim, W., Fatima, Z., Hussain, S., Habib ur Rehman, M., Khan, M.A., Hasanuzzaman, M., Fahad, S., Boote, K.J., Hoogenboom, G., 2017. Quantification the impacts of climate change and crop management on phenology of maize-based cropping system in Punjab, Pakistan. Agric. For. Meteorol. 247, 42–55.

Abu-Asab, M.S., Peterson, P.M., Shetler, S.G., Orli, S.S., 2001. Earlier plant flowering in spring as a response to global warming in the Washington, DC area. Biodivers. Conserv. 10, 597–612.

Afzaal, M., Haroon, M.A., Zaman, Qamarul, 2009. Interdecadal oscillations and the warming trend in the area-weighted annual mean temperature of Pakistan. Pak. J. Meteorol. 6 (11), 13–19.

Ahmad, A., Ashfaq, M., Rasul, G., Wajid, S.A., Khaliq, T., Rasul, F., Saeed, U., Habib ur Rahman, M., Hussain, J., Baig, I.A., Naqvi, S.A.A., Bokhari, S.A.A., Ahmad, S., Naseem, W., Hoogenboom, G., Valdivia, R.O., 2015. Impact of climate change on the rice-wheat cropping system of Pakistan. In: In: Hillel, D., Rosenzweig, C. (Eds.), Handbook of Climate Change and Agro-Ecosystems, vol. 3 Imperial College Press and the American Society of Agronomy pp. 219–258.

Ahmad, S., Abbas, Q., Abbas, G., Fatima, Z., Atique-ur-Rehman, Naz S., Younis, H., Khan, R.J., Nasim, W., Habib ur Rehman, M., Ahmad, A., Rasul, G., Khan, M.A., Hasanuzzaman, M., 2017a. Quantification of climate warming and crop management impacts on cotton phenology. Plants 6, 1–16.

Ahmad, S., Abbas, G., Fatima, Z., Khan, R.J., Anjum, M.A., Ahmed, M., Khan, M.A., Porter, C.H., Hoogenboom, G., 2017b. Quantification of the impacts of climate warming and crop management on canola phenology in Punjab, Pakistan. J. Agron. Crop Sci. 203, 442–452.

Ahmad, S., Ahmad, A., Ali, H., Hussain, A., Garcia y Garcia, A., Khan, M.A., Zia-Ul-Haq, M., Hasanuzzaman, M., Hoogenboom, G., 2013. Application of the CSM-CERES-Rice model for evaluation of plant density and irrigation management of transplanted rice for an irrigated semiarid environment. Irrig. Sci. 31, 491–506.

Ahmad, S., Ahmad, A., Soler, C.M.T., Ali, H., Zia-Ul-Haq, M., Anothai, J., Hussain, A., Hoogenboom, G., Hasanuzzaman, M., 2012. Application of the CSM-CERES-Rice model for evaluation of plant density and nitrogen management of fine transplanted rice for an irrigated semiarid environment. Precis. Agric. 13, 200–218.

Ahmad, S., Nadeem, M., Abbas, G., Fatima, Z., Khan, R.J.Z., Ahmed, M., Ahmad, A., Rasul, G., Khan, M.A., 2016. Quantification of the effects of climate warming and crop management on sugarcane phenology. Clim. Res. 71, 47–61.

Ahmed, M., Akram, M.N., Asim, M., Aslam, M., F-u, Hassan, Higgins, S., Stöckle, C.O., Hoogenboom, G., 2016. Calibration and validation of APSIM-wheat and CERES-wheat for spring wheat under rainfed conditions: models evaluation and application. Comput. Electron. Agric. 123, 384–401.

Ahmed, M., Hassan, F.-u, Van Ogtrop, F.F., 2014. Can models help to forecast rainwater dynamics for rainfed ecosystem? Weather Clim. Extrem. 5–6, 48–55.

Ahmed, M., Hassan, F.-u, Razzaq, A., Akram, M.N., Aslam, M., Ahmad, S., Zia-Ul-Haq, M., 2011. Is photothermal quotient determinant factor for spring wheat yield. Pak. J. Bot. 43 (3), 1621–1627.

Amin, A., Nasim, W., Mubeen, M., Sarwar, S., Urich, P., Ahmad, A., Wajid, A., Khaliq, T., Rasul, F., Hammad, H.M., Rehmani, M.I.A., Mubarak, H., Mirza, N., Wahid, A., Ahmad, S., Fahad, S., Ullah, A., Khan, M.N., Ameen, A., Amanullah, Shahzad, B., Saud, S., Alharby, H., Ata-Ul-Karim, S.T., Adnan, M., Islam, F., Ali, Q.S., 2018. Regional climate assessment for temperature and precipitation in Southern Punjab (Pakistan) using SimCLIM climate model for different temporal scales. Theor. Appl. Climatol. 131, 121–131. https://doi.org/10.1007/s00704-016-1960-1.

Aslam, M.A., Ahmed, M., Stöckle, C.O., Higgins, S.S., Fu, Hassan, Hayat, R., 2017. Can growing degree days and photoperiod predict spring wheat phenology? Front. Environ. Sci. 5, 57. https://doi.org/10.3389/fenvs.2017.00057.

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Glob. Change Biol. 17 (2), 997–1012.

Bindi, M., Moriondo, M., 2005. Impact of a 2°C global temperature rise on the Mediterranean region: agriculture analysis assessment. Climate Change Impacts in the Mediterranean Resulting From a 2°C Global Temperature Rise. A WWF Report. . http://assets.panda.org/downloads/medreportfinal8july05.pdf.

Bokhari, S.A.A., Rasul, G., Ruane, A.C., Hoogenboom, G., Ahmad, A., 2017. The past and future changes in climate of the rice-wheat cropping zone in Punjab, Pakistan. Pak. J. Meteorol. 13 (26), 9–23.

Brancourt-Hulmel, M., Doussinault, G., Lecomte, C., Berard, P., Buanec, B.L., Torrtet, M., 2003. Genetic improvement of agronomic traits of winter wheat cultivars released in France from 1946 to 1992. Crop Sci. 43, 37–45.

Brown, M.E., De Beurs, K.M., Marshall, M., 2012. Global phenological response to climate change in crop areas using satellite remote sensing of vegetation, humidity and temperature over 26 years. Remote Sens. Environ. 126, 174–183.

Chmielewski, F.-M., Muller, A., Bruns, E., 2004. Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. Agric. For. Meteorol. 121 (1–2), 69–78.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., Schwartz, M.D., 2007. Shifting plant phenology in response to global change. Trends Ecol. Evol. 22 (7), 357–365.

Craufurd, P.Q., Wheeler, T.R., 2009. Climate change and the flowering time of annual crops. J. Exp. Bot. 60 (9), 2529–2539.

Ding, Y.H., Ren, G.Y., Shi, G.Y., et al., 2006. National assessment report of climate change (I): climate change in China and its future trend. Adv. Clim. Change Res. 2 (1), 3–8.

Ellwood, E., Diez, J., Ibá˜nez, I., Primack, R., Kobori, H., Higuchi, H., Silander, J., 2012. Disentangling the paradox of insect phenology: are temporal trends reflecting the response to warming? Oecologia 168, 1161–1171.

Estrella, N., Sparks, T.H., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. Glob. Change Biol. 13, 1737–1747.

Figueiredo, N., Carranca, C., Trindade, H., Pereira, J., Goufo, P., Coutinho, J., Marques, P., Maricato, R., de Varennes, A., 2015. Elevated carbon dioxide and temperature effects on rice yield, leaf greenness, and phenological stages duration. Paddy Water Environ. 13 (4), 313–324.

Fitter, A.H., Fitter, R.S.R., 2002. Rapid changes in flowering time in British plants. Science 296, 1689–1691.

Gordo, O., Sanz, J.J., 2005. Phenology and climate change: a long-term study in a Mediterranean locality. Oecologia 146 (3), 484–495.

Gouache, D., Bris, X.L., Bogard, M., Deudon, O., Pagé, C., Gate, P., 2012. Evaluating agronomic adaptation options to increasing heat stress under climate change during wheat grain filling in France. Eur. J. Agron. 39, 62–70.

Guhey, A., Patel, K.C., Saxena, R., Verulker, S.B., 2009. Influence of temperature and humidity on physiology, phenology and yield traits of rice. J. Rice Res. 2 (1), 1–15.

He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W., Jin, N., Yu, Q., 2015. Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. Agric. For. Meteorol. 200, 135–143.

Hoffmann, A.A., Sgrò, C.M., 2011. Climate change and evolutionary adaptation. Nature 470, 479–485.

Hoogenboom, G., Porter, C.H., Shelia, V., Boote, K.J., Singh, U., White, J.W., Hunt, L.A., Ogoshi, R., Lizaso, J.I., Koo, J., Asseng, S., Singels, A., Moreno, L.P., Jones, J.W., 2017. Decision Support System for Agrotechnology Transfer (DSSAT), Version 4.7. DSSAT Foundation, Gainesville, Florida, USA. http://dssat.net.

Hu, Q., Weiss, A., Feng, S., Baenziger, P.S., 2005. Earlier winter wheat heading dates and warmer spring in the US Great Plains. Agric. For. Meteorol. 135, 284–290.

IPCC, 2014. Climate change 2014. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Iqbal, M.M., Goheer, M.A., Noor, S.A., Sultana, H., Salik, K.M., Khan, A.M., 2009. Climate Change and Rice Production in Pakistan: Calibration, Validation and Application of CERES-Rice Model, GCISC-RR-15. Global Change Impact Studies Centre (GCISC), Islamabad, Pakistan pp. 1–25.

Islam, M.R., Sikder, S., 2011. Phenology and degree days of rice cultivars under organic culture. Bangladesh J. Bot. 40 (2), 149–153.

Jagadish, S.V.K., Craufurd, P.Q., Wheeler, T.R., 2008. Phenotypingparents of mapping populations of rice for heat tolerance during anthesis. Crop Sci. 48 (3), 1140–1146.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3–4), 235–265.

Kariyeva, J., Willem, J.D., van Leeuwen, W.J.D., Woodhouse, C.A., 2012. Impacts of climate gradients on the vegetation phenology of major land use types in Central Asia (1981–2008). Front. Earth Sci. 6 (2), 206–225.
Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM: a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.
Li, K., Yang, X., Tian, H., Pan, S., Liu, Z., Lu, S., 2016. Effects of changing climate and cultivar on the phenology and yield of winter wheat in the North China Plain. Int. J. Biometeorol. 60 (1), 21–32.
Li, Z., Yang, P., Tang, H., Wu, W., Yin, H., Liu, Z., Zhang, L., 2014. Response of maize phenology to climate warming in Northeast China between 1990 and 2012. Reg. Environ. Change 14 (1), 39–48.
Linderholm, H.W., 2006. Growing season changes in the last century. Agric. For. Meteorol. 137 (1), 1–14.
Liu, L., Wang, E., Zhu, Y., Tang, L., 2012. Contrasting effects of warming and autonomous breeding on single-rice productivity in China. Agric. Ecosyst. Environ. 149, 20–29.
Liu, Y., Wang, E., Yang, X., Wang, J., 2010. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Glob. Change Biol. 16, 2287–2299.
Liu, Y., Chen, Q., Ge, Q., Dai, J., Qin, Y., Dai, L., Zou, X., Chen, J., 2018. Modelling the impacts of climate change and crop management on phenological trends of spring and winter wheat in China. Agric. For. Meteorol. 248, 518–526.
Liu, Z., Hubbard, K.G., Lin, X., Yang, X., 2013. Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. Glob. Change Biol. 19, 3481–3492.
Lobell, D.B., Sibley, A., Ortiz-Monasterio, J.I., 2012. Extreme heat effects on wheat senescence in India. Nat. Clim. Change 2, 186–189.
Madan, P., Jagadish, S.V., Craufurd, P.Q., Fitzgerald, M., Lafarge, T., Wheeler, T.R., 2012. Effect of elevated CO_2 and high temperature on seed set and grain quality of rice. J. Exp. Bot. 63 (10), 3843–3852.
Martín, M.M.-S., Olesen, J.E., Porter, J.R., 2014. A genotype, environment and management (G × E × M) analysis of adaptation in winter wheat to climate change in Denmark. Agric. For. Meteorol. 187, 1–13.
Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kubler, K., Bissolli, P., Braslavska, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, A., Defila, C., Donnelly, A., Fililla, Y., Jatczak, K., Mage, F., Mestre, A., Nordli, O., Penuelas, J., Pirinen, P., Remisova, V., Scheifinger, H., Striz, M., Susnik, A., van Vliet, A.J.H., Wielgolaski, F.-E., Zach, S., Zust, A., 2006. European phenological response to climate change matches the warming pattern. Glob. Change Biol. 12 (10), 1969–1976.
Moriondo, M., Bindi, M., 2007. Impact of climate change on the phenology of typical Mediterranean crops. Ital. J. Agrometrol. 3, 5–12.
Mueller, V., Gray, C., Kosec, K., 2014. Heat stress increases long-term human migration in rural Pakistan. Nat. Clim. Change 4, 182–185.
Neil, K., Wu, J., 2006. Effects of urbanization on plant flowering phenology: a review. Urban Ecosyst. 9 (3), 243–257.
Ortiz, R., Sayre, K.D., Govaerts, B., Gupta, R., Subbarao, G.V., Ban, T., Hodson, D., Dixon, J.M., Ortiz-Monasterio, J.I., Reynolds, M., 2008. Climate change: can wheat beat the heat? Agric. Ecosys. Environ. 126 (1–2), 46–58.
Oteros, J., Garcia-Mozo, H., Botey, R., Mestre, A., Galan, C., 2015. Variations in cereal crop phenology in Spain over the last twenty-six years (1986–2012). Clim. Change 130, 445–458.
Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. U. S. A. 101 (27), 9971–9975.
Rani, B.A., Maragatham, N., 2013. Effect of elevated temperature on rice phenology and yield. Ind. J. Sci. Technol. 6, 5095–5097.
Rasul, G., Mahmood, A., Sadiq, A., Khan, S.I., 2012. Vulnerability of the Indus delta to climate change in Pakistan. Pak. J. Meteorol. 8, 89–107.
Rezaei, E.E., Siebert, S., Ewert, F., 2015. Intensity of heat stress in winter wheat? Phenology compensates for the adverse effect of global warming. Environ. Res. Lett. 10 (2), 024012.
Sacks, W.J., Kucharik, C.J., 2011. Crop management and phenology trends in the US corn belt: impacts on yields, evapotranspiration and energy balance. Agric. For. Meteorol. 151, 882–894.
Sadras, V.O., Monzon, J.P., 2006. Modelled wheat phenology captures rising temperature trends: shortened time to flowering and maturity in Australia and Argentina. Field Crops Res. 99, 136–146.
Saseendran, S.A., Singh, K.K., Rathore, L.S., Singh, S.V., Sinha, S.K., 2000. Effects of climate change on rice production in the Tropical humid climate of Kerala, India. Clim. Change 44 (4), 495–514.
Semenov, M.A., 2009. Impacts of climate change on wheat in England and Wales. J. R. Soc. Interface 6, 343–350.
Siebert, S., Ewert, F., 2012. Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length. Agric. For. Meteorol. 152, 44–57.
Sparks, T.H., Croxton, P.J., Collinson, N., Taylor, P.W., 2005. Examples of phenological change, past and present, in UK farming. Ann. Appl. Biol. 146, 531–537.
Sparks, T.H., Jeffree, E.P., Jeffree, C.E., 2000. An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. Int. J. Biometeorol. 44, 82–87.
Talukder, A.S.M.H.M., McDonald, G.K., Gill, G.S., 2013. Effect of short-term heat stress prior to flowering and at early grain set on the utilization of water-soluble carbohydrate by wheat genotypes. Field Crops Res. 147, 1–11.
Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y., Zhang, Z., 2006. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric. For. Meteorol. 138 (1–4), 82–92.
Tao, F., Zhang, S., Zhang, Z., 2012. Spatiotemporal changes of wheat phenology in China under the effects of temperature, day length and cultivar thermal characteristics. Eur. J. Agron. 43, 201–212.
Tao, F., Zhang, S., Zhang, Z., Rötter, R.P., 2014. Maize growing duration was prolonged across China in the past three decades under the combined effects of temperature, agronomic management, and cultivar shift. Glob Change Biol. 20 (12), 3686–3699.
Tao, F., Zhang, Z., Shi, W., Liu, Y., Xiao, D., Zhang, S., Zhu, Z., Wang, M., Liu, F., 2013. Single rice growth period was prolonged by cultivars shifts, but yield was damaged by climate change during 1981–2009 in China, and late rice was just opposite. Glob. Change Biol. 19 (10), 3200–3209.
Tariq, M., Ahmad, S., Fahad, S., Abbas, G., Hussain, S., Fatima, Z., Wajid, N., Mubeen, M., Habib ur Rehman, M., Khan, M.A., Adnan, M., Wilkerson, C.J., Hoogenboom, G., 2018. The impact of climate warming and crop management on phenology of sunflower-based cropping systems in Punjab, Pakistan. Agric. For. Meteorol. 256–257, 270–282.
van Ogtrop, F., Ahmad, M., Moeller, C., 2014. Principal components of sea surface temperatures as predictors of seasonal rainfall in rainfed wheat growing areas of Pakistan. Meteorol. Appl. 21 (2), 431–443.
van Oort, P.A.J., Zhang, T., de Vries, M.E., Heinemannd, A.B., Meinkea, H., 2011v. Correlation between temperature and phenology prediction error in rice (*Oryza sativa* L.). Agric. For. Meteorol. 151 (12), 1545–1555.
Visser, M.E., Both, C., 2005. Shifts in phenology due to global change: the need for a yardstick. Proc. R. Soc. 272, 2561–2569.
Wang, H.L., Gan, Y.T., Wang, R.Y., Niu, J.Y., Zhao, H., Yang, Q.G., Li, G.C., 2008. Phenological trends in winter wheat and spring cotton in response to climate changes in northwest China. Agric. For. Meteorol. 148 (8–9), 1242–1251.
Wang, J., Wang, E., Feng, L., Yin, H., Yu, W., 2013. Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. Field Crops Res. 144, 135–144.
Williams, T.A., Abberton, M.T., 2004. Earlier flowering between 1962 and 2002 in agricultural varieties of white clover. Oecologia 138, 122–126.
Xiao, D., Qi, Y., Shen, Y., Tao, F., Moiwo, J.P., Liu, J., Wang, R., Zhang, H., Liu, F., 2016. Impact of warming climate and cultivar change on maize phenology in the last three decades in North China Plain. Theor. Appl. Climatol. 124 (3), 653–661.
Xiao, D., Tao, F., Liu, Y., Shi, W., Wang, M., Liu, F., Zhang, S., Zhu, Z., 2013. Observed changes in winter wheat phenology in the North China Plain for 1981–2009. Int. J. Biometeorol. 57 (2), 275–285.
Yao, F., Xu, Y., Lin, E., Yokozawa, M., Zhang, J., 2007. Assessing the impacts of climate change on rice yields in the main rice areas of China. Clim. Change 80, 395–409.
Zhang, S., Tao, F., 2013. Modeling the response of rice phenology to climate change and variability in different climatic zones: comparisons of five models. Eur. J. Agron. 45, 165–176.
Zhang, T., Huang, Y., Yang, X., 2013. Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. Glob Change Biol. 19, 563–570.
Zhao, G., Bryan, B.A., Song, X., 2014. Sensitivity and uncertainty analysis of the APSIM-Wheat model: interactions between cultivar, environmental, and management parameters. Ecol. Model. 279, 1–11.